NAIC-ID(RS)T-0477-95

NATIONAL AIR INTELLIGENCE CENTER

COMMUNICATION JAMMING OF DIRECT-SPREAD SPECTRUM MODULATION

by

Xu Muxun

HUMAN TRANSLATION

NAIC-ID(RS)T-0477-95 13 February 1996

MICROFICHE NR: 96C000087

COMMUNICATION JAMMING OF DIRECT-SPREAD SPECTRUM MODULATION

By: Xu Muxun

English pages: 27

Source: Unknown

Country of origin: China
Translated by: Leo Kanner Associates
F33657-88-D-2188
Requester: NAIC/TAER/Frank F. Scenna
Approved for public release: distribution unlimited.

THIS TRANSLATION IS A RENDITION OF THE ORIGINAL FOREIGN TEXT WITHOUT ANY ANALYTICAL OR EDITORIAL COMMENT STATEMENTS OR THEORIES ADVOCATED OR IMPLIED ARE THOSE OF THE SOURCE AND DO NOT NECESSARILY REFLECT THE POSITION OR OPINION OF THE NATIONAL AIR INTELLIGENCE CENTER.	PREPARED BY: TRANSLATION SERVICES NATIONAL AIR INTELLIGENCE CENTER WPAFB, OHIO

GRAPHICS DISCLAIMER

All figures, graphics, tables, equations, etc. merged into this translation were extracted from the best quality copy available.

COMMUNICATION JAMMING OF DIRECT-SPREAD SPECTRUM MODULATION

Xu Muxun

Institute Number 36, Ministry of Electronics
Industry, Jiaxin 314001

Editor's comment: When this article in draft form was being evaluated, a number of specialists stated different views about some concepts, viewpoints, and techniques in the article. After an exchange of views between the editing department and the author, on the principle of respecting the author's views and for the academic contest of different approaches, his views are published here unmodified. Readers' comments in this regard are welcome.

ABSTRACT: The article studies spot-jamming of waveforms; the author points out that this jamming is still in the exploratory study stage. The article stresses investigating correlation jamming, single-frequency jamming, and unmodulated continuous-wave jamming. These kinds of jamming involve barrage jamming of direct-spread spectrum modulation. Barrage jamming is an effective jamming system against present-day direct-spread spectrum modulation. Single-frequency jamming is not the optimal absolute kind of jamming; however, correlation jamming and unmodulated continuous-wave jamming are the optimal choices of absolute jamming. Correlation jamming is suitable in applying barrage jamming on multiple message channels in direct-spread spectrum modulation in adjacent carrier frequencies. However,

the unmodulated continuous-wave jamming is adaptable to apply barrage jamming on fixed-frequency modulation, frequency-hopper modulation, direct-frequency modulation, and hybrid spread-spectrum modulation of multiple widely distributed message channels with respect to the signal carrier frequency.

KEY WORDS: modulation jamming, direct spread-spectrum modulation, spot jamming, barrage jamming.

I. Spot Jamming and Barrage Jamming in Spread-spectrum Modulation

In executing modulation jamming, this can be divided into two major jamming systems; spot jamming and barrage jamming [1]. When we seek to fixed-frequency modulation (conventional modulation), it can be seen that spot jamming is narrowband jamming in the frequency domain; however, barrage jamming is wideband jamming.

With the advent of spread-spectrum modulation, various spread-spectrum modulation signals can overlap with each other in the frequency domain. However, receivers of various signal channels separately receive their spread-spectrum modulation signals based on different pseudocode patterns in the spread spectrum. Therefore, for jamming execution, we cannot classify on the basis of jamming frequency width, as was done in the previous cases. Based on the theory of optimal jamming, the spread-spectrum patterns of optimal spot jamming are identical to the spread-spectrum patterns of spread-spectrum jamming in this particular signal channel. Thus, this serves only to apply effective jamming of the spread spectrum modulation on this particular signal channel, without attaining effective jamming on spread-spectrum modulation in other message channels. With respect to optimal barrage jamming of spread-spectrum modulation, jamming patterns should have the same optimal jamming effect of spread-spectrum jamming in the various signal channels.

Classification of two major systems of this accurate modulation jamming is helpful to insightful research, especially

so for research on spread-spectrum modulation jamming. We can make the following classification on spread-spectrum modulation jamming with sequence:

spot jamming: waveform overlap jamming (waveform spot jamming)

barrage (interrupted) jamming

correlation (pseudocode modulation) jamming (partial barrage jamming)

single-frequency (narrowband) jamming (direct barrage jamming)

unmodulated continuous-wave jamming (overall barrage jamming).

II. Waveform Spot Jamming of Direct-Spread Spectrum Modulation

At present, automatically, rapidly, and accurately executing effective spot jamming with fixed-frequency modulation will force the modulation source to develop a spread-spectrum modulation in order to counter such spot jamming. When the jammer still wishes to execute spot jamming, then he is disadvantaged.

Spot jamming by the jammer should master the particular pseudocode pattern (sequence) of the particular direct-spread spectrum modulation to be jammed. During jamming, the jamming signals modulated by this pseudocode patterns are adopted to execute spot jamming of the modulation. In the frequency domain, the jamming carrier frequency overlaps with the signal carrier frequency; the jamming frequency width matches the signal frequency width. In the time domain, moreover, the pseudocode rate and the jamming pseudocode sequence is the same as the pseudocode rate and pseudocode sequence of the signal. In other words, the jamming time-domain waveform, after being modulated with the pseudocode sequence, is the same as the time domain waveform of direct-spread spectrum signals. Thus, we call this

spot-jamming waveform overlap jamming, or waveform spot jamming. This requires real-time decoding on the pseudocode patterns and the reconnaissance and reception of direct-spread spectrum signals. We know that decoding on information of confidential signals is applied after capturing confidential messages. However, real-time reconnaissance, reception, and decoding of signal carriers require much greater technical signals compared to message decoding. In particular, in a high-signal-density environment, various signals are mixed and overlapped. There is even greater difficulty in real-time decoding of the signal carrier. Moreover, from the optimal jamming theory, the jamming parameters should meet the following conditions in order to attain effective jamming:

(1) the jamming carrier frequency f_{j1} and the signal carrier frequency fS to be jammed, $f_{j1} \approx fs$, $|\triangle f_{j1}| = |f_{j1} - fs| < 0.1B_m$

(2) the noise modulation frequency width B_{m1} of jamming is approximately equal to the signal frequency width B_m of the signal, $B_{m1} \approx B_m$

(3) At the input terminal of the receiver, the jamming pseudocode sequence $p_1(t)$ is the same and is synchronous with the pseudocode sequence $p_0(t)$ of the receiver's local oscillator:

$$p_1(t) = p_0(t)$$

Thus, the jamming energy is like the signal energy since it can unrestrictedly pass through the narrow-band filter of the receiver. In other words, during demodulation of spread spectrum, no restraining function is applied to jamming. Here, for effective jamming, the jamming power at the input terminal of the receiver is only required to be equal to the signal power. Its separation coefficient K_{j1} (jamming-to-signal power ratio) is approximately 1; $K_{j1}=P_{J1}/P_{S1}\approx 1$.

We may know that in order to reduce the pseudosynchronous probability of pseudo direct-spread spectrum modulation, a pseudocode sequence with good autocorrelation performance is adopted. The autocorrelation function is best to have only one

peak value. Or, also there are side loops in the autocorrelation function; it is required that the number of side loops should be few. In addition, the peak value of the side loops is much smaller than the peak value of the main loop (at zero time lag) [3]. For example, there is only a peak value for the autocorrelation function of the maximum-length linear sequence (m sequence). When the time delay is zero, the autocorrelation value is equal to the pseudocode sequence length, $R(0)=M$. However, when the time delay is greater than the pseudocode width ($|\tau|>T_p$, the autocorrelation value is only -1. This pseudocode sequence is applied to direct-spread spectrum modulation. Moreover, the sequence has very high capability of resisting waveform spot jamming. When the jamming pseudocode sequence $P_1(t)$ is not synchronous with the signal pseudocode sequence $P_0(t)$, let us assume that the time delay is τ, and $P_1(t-\tau)=P_0(t)$, then $P_1(t)$ is not equal to $P_0(t)$. At this stage, the product of $P_1(t) \cdot P_0(t)$ is not consistently +1 in the time domain, appearing as +1 sometimes, and -1 at other times. Then, after frequency mixing of the jamming signal, the frequency spectrum of the intermediate-frequency signals of the output jamming is still wideband, and only a very small part of the jamming energy passes through the narrowband filter. Therefore, there is a very high treatment gain for the modulation receiver on this same, but not synchronous, pseudocode modulated jamming.

With respect to this aspect, we should conduct the effective optimal spot jamming of the military direct-spread spectrum modulation:

(1) When synchronizing has been established in direct-spread spectrum modulation, and messages are beginning to be transmitted, the probability is very low that effective jamming should be applied. The longer the length M of the pseudocode sequence, the smaller is the effective jamming probability $\phi_j=1/M$.

(2) Before synchronicity is established in direct-spread spectrum modulation, and for effective jamming, the jammer should at least search, intercept, and sort the time T_1 of the signal for control and stimulation in order to start the summation of the jamming time T_2. Then, adding the summation of the reconnaissance path R_1 and the jamming path R_2, with the subtraction of the required transmission time t_3 of the modulation path R3, the required time T_3 should be smaller than the signal search synchronizing time T_S of the modulation receiving side.

$$T_1 + T_2 + T_3 < T_s$$

$$T_3 = \frac{1}{C}(r_1 + r_2 - r_3)$$

In the equations, C is the propagation speed of electronic waves.

(3) Under the situation of fixed technical parameters of modulation frequency for direct-spread spectrum modulation, advanced jamming should be executed. In other words, before the transmitting of signals by the modulation side, or before starting and receiving by a receiver, spot waveform jamming is sent for this message channel; thus, the jammer is required to know the exact beginning modulation time of the jammer's enemy.

From the foregoing analysis, generally the effective waveform spot jamming of direct-spread spectrum modulation requires much stronger technical signals [4] compared to the effective waveform spot jamming of frequency-hopper modulation. At present, this waveform spot jamming is still in the exploratory study stage. We will see that to intensify countermeasures for waveform spot jamming by the modulation side, direct-spread spectrum modulation may not periodically change the signal carrier frequency; or the signal carrier frequency is changed at each time of modulation; or by hybridizing with frequency-hopper technology, continually and automatically change

the carrier frequency at each time of modulation. Furthermore, the signal carrier can be encrypted. If the fundamental keying quantity is increased, the nonlinearity of the pseudocode is intensified, and the pseudocode sequence of direct-spread spectrum patterns is intensified, along with some other measures in order to increase the technical difficulties for searching and interrupting the direct-spread spectrum signals and technical difficulties of real-time decryption and sorting of the signal pseudocode sequence by the jammer. On the other hand, if in some particular case, such as jamming against GPS, since its pseudocode has been made public, then it is possible to carry out the effective waveform spot jamming [5] on the direct-spread spectrum modulation. At this point, real-time reconnaissance and reception can be made to the direct-spread spectrum modulation in order to intercept the message information. At some key instance, effective jamming can be applied; in this way, the required jamming power is the lowest.

Therefore, in the author's view, confidential modulation appears on message description in modulation. Then, successively, jump frequency, direct-broadcast and other spread spectrum modulation appear with decryption of the modulation carrier; furthermore, the decryption capability is continuously upgraded. This is the technical superiority of the communication side at present. As a jammer, it is not supposed to stop on the concept of spot jamming for fixed-frequency modulation, and only emphasize the development on spot jamming against spread-spectrum modulation, but the jammer should explore the technical superiority of the jamming side. Decrypted modulation appears by decrypting the communicated message. Thus, people have realized that more jamming should be adopted in order to disturb the modulation to substitute for stealing of the communicated message by modulation reconnaissance and decryption. However, various kinds of spread spectrum modulation appear in the present decryption of the modulation carrier. Thus, the author proposes

that more barrage jamming should be applied to disturb multiple modulation channels in a frequency band, to substitute for the disturbance with spot jamming on the modulation of some particular signal channel. Especially with respect to direct-spread spectrum modulation, the most effective jamming system at present is barrage (interruption) jamming.

III. Correlation barrage jamming against direct-spread spectrum modulation

The jammer is not required to have the pseudocode sequence of direct-spread spectrum modulation of a particular message channel, but only is required to have the patterns of the pseudocode sequence generator used by the direct-spread spectrum station of some series; this is the pattern of the pseudocode sequence used to execute correlation jamming, which adopts the pseudocode modulation jamming system. The jamming carrier frequency should be close to the signal center frequency; the jamming pseudocode rate should be close to the signal pseudocode rate. Moreover, the pseudocode sequence and the cross-correlation between signal and pseudocode sequence should be intensified as much as possible.

Assume that the correlation jamming at the input terminal of the modulation receiver is given by the following formula:

$$j_2(t) = J_2 \cdot m_2(t) \cdot p_2(t) \cdot \cos 2\pi f_{j2} t$$

J_2 is the oscillation amplitude of jamming

$m_2(t)$ is the two-element numerical modulation sequence, $m_2(t) = +1$ or -1

$p_2(t)$ is the two-element pseudocode sequence, $p_2(t) = +1$ or -1

f_{j2} is the carrier frequency of jamming.

Assume that the local oscillator signal is given by the following formula:

$$d(t) = D \cdot p_0(t)\cos 2\pi f_0 t$$

D is the oscillation amplitude of the local oscillator signal

$p_0(t)$ is the pseudocode sequence of local oscillator

f_0 is the center frequency of the local oscillator

By multiplying the jamming and the local oscillator signal of the receiver, after frequency mixing, the jamming intermediate-frequency signal (the part of the slip frequency) is

$$j_{i2}(t) = \frac{1}{2} J_2 \cdot D \cdot m_2(t) \cdot P_2(t) \cdot p_0(t) \cdot \cos 2\pi(f_0 - f_{j2})t$$

Since the signal and the jamming pseudocode sequence is not the same, then the product $p_2(t) \cdot p_0(t)$ does not consistently stay at +1 in the time domain, but sometimes +1 and at other times, -1. Then the jamming frequency spectrum is wider after frequency mixing. When the correlation is increased, the jump times between +1 and -1 are reduced, at a slowing down rate. Then the energy of the jamming intermediate-frequency signal concentrates toward the center frequency, and the jamming frequency width becomes narrower. However, higher jamming energy passes through the narrowband filter.

When the jamming carrier frequency approaches the signal center frequency, the center frequency ($f_{i2}=f_0-f_{j2}$) will not deviate too far from the center frequency f_i of the narrowband filter, and the jamming energy passes through the narrowband filter.

In actual direct-spread spectrum modulation, the applied pseudocode sequence is very long. For simplicity in analysis, a short pseudocode sequence is adopted. Assume that the maximum linear pseudocode sequence of [5,3] of 31 digits is adopted for the local oscillator of the receiver, in the case of direct spread-spectrum modulation, the sequence D(i) is:

1	1	1	1	1	0	0	0	1	1	0	1	1	1	0	1	0	1	0	0	0	0	1	0	0	1	0	1	1	0	0

However, when the maximum linear pseudocode sequence of 31 digits is applied for jamming [5,2], the sequence $J_2(i)$ is:

1	1	1	1	1	0	0	1	1	0	1	0	0	1	0	0	0	0	1	0	1	0	1	1	1	0	1	1	0	0	0

The [5, 3] sequence is the mirror image of [5, 2], and vice versa. In other words, the reverse operation in time sequence of either of the two above-mentioned sequences is another sequence.

The cross-correlation function (of both sequences)

$$R(\tau) = \sum_{i=1}^{31} D(i) J_2(i-\tau) \ :$$

$\tau(T_p)$	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
$R(\tau)$	3	7	3	−9	3	7	−9	7	7	11	−1	−1	3	−1	−5	3	−9	−1	−5	−5	3	3	3	−9	7	−1	3	−5	−9	−5	3

The following table shows the various cross-correlation values and their probabilities of appearing.

$R(\tau)$	−9	−5	−1	3	7	11
* 概率	5/31	5/31	5/31	10/31	5/31	1/31
%	16	16	16	32	16	4

*Probability

The binary numerical sequence $m_2(t)$ is used to modulate the correlation jamming; at times $m_2(t)$ is +1 and at other times, −1. Then the jamming pseudocode sequence is the [5, 2] sequence at times, and the reverse value of the [5, 2] sequence, at other times. The following table shows the cross-correlation value of the [5, 3] sequence and its probabilities of appearance:

$R(\tau)$	−11	−9	−7	−5	−3	−1	1	3	5	7	9	11
%	2	8	8	8	16	8	8	16	8	8	8	2

The cross-correlation values correspond to the output jamming energy after the jamming is received correlatively. By taking the mean value, $R_0 = \sum_{\tau=0}^{30} R(\tau)/31 = 4.9$, then the output mean jamming power corresponds to 4.9. However, the signal output is 31, and now the output jamming power is approximately 4.9/31 (≈1/6) of the signal output power. For effective jamming, the jamming power at the input terminal of the communication receiver should be equal to six times the signal power; in other words, the suppression coefficient is 6.

Based on the foregoing analysis, we must assume that the length of each signal code element is equal to the pseudocode sequence length N=M. Generally, however, the modulation in transmission of the direct spread spectrum adopts a long pseudocode sequence; the length of each signal code element is considerably less than the length of the pseudocode sequence, N<<M. For sake of simplicity in the analysis, assume that the local oscillation of the receiver still adopts the [5, 3] sequence of the maximum linear pseudocode of 31 digit-long maximum linear pseudocode. However, jamming also adopts the maximum [5, 2] sequence of the linear pseudocode of 31 digit length. However, the length of each signal code element is a 5-digit pseudocode element, not the 31-digit pseudocode element. When correlation is received, the length of each signal code element (that is, five pseudocode elements) in the jamming energy cumulative process, we can see that at times the jamming state may reach full correlation. In other words, within a signal code element, patterns of two sequences are the same; the jamming energy is 5, since it is equal to signal energy. At times, the jamming state is in partial correlation, if the jamming energy is 3. At other times, the jamming state is not correlated since the jamming energy is 1. We know that after fixing the time lag of two sequences, 31 jamming states may appear; this corresponds to the correlation state of patterns in five adjacent digits corresponding to any adjacent 5-digit patterns and corresponding

to a jamming sequence of the local oscillation sequence. However, there are 31 time delay states in both sequences. For example, the following table lists 31 jamming states of some corresponding sections with different time delays.

$\tau(T_p)$	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	0
$R(\tau)$	−1	1	−1	−3	−3	1	5	−1	−3	1	3	−3	−1	−1	1	1	−1	1	−1	3	3	−3	1	1	−1	3	1	−5	−1	3	1

With respect to statistics of cross-correlation values of a large number of jamming states, the output mean jamming power approximately corresponds to 2, which is 2/5 of the signal output power, approximately corresponding to 12/31, which is better than 4.9/31. Thus, when adopting correlation jamming, jamming against direct-spread spectrum modulation in communication of N<<M, the jamming effectiveness is better than jamming against direct-spread spectrum modulation in communication of N=M. With statistical analysis, when the maximum linear sequence is adopted in direct-spread spectrum modulation in communication, and N<M, for correlation jamming the lowest separation coefficient is approximately $(N)^{1/2}$.

With respect to jamming, for optimal correlation jamming, we should study the jamming pseudocode sequence [6] of generating the maximum cross-correlation value for the signal pseudocode sequence. The greater the cross-correlation of the sequence, the better is the jamming effectiveness. For effective jamming, the required jamming power is smaller.

This correlation jamming is of the barrage type jamming because the pseudocode sequence correlates with various pseudocode sequence of the communication station operating the direct spread-spectrum modulation of certain series. The station can execute correlation jamming against various direct spread-spectrum modulation in communication of this series. When the multiple channels with direct spread-spectrum modulation of this series execute code division multiple address communication in

the same region and at the same carrier frequency, by adopting this correlation jamming by a single jamming device, effective barrage type jamming can be carried out simultaneously on all this communication with direct spread-spectrum modulation.

IV. Single-Frequency (or Narrowband) Barrage Type Jamming in Communication with Direct Spread-Spectrum Modulation

With respect to barrage type jamming against communication with direct spread-spectrum modulation, in executing jamming, all communication is jammed with direct spread-spectrum modulation in the frequency band, but does not affect the fixed-frequency or frequency-hopper communication in this jamming frequency band. We known that the instantaneous frequency band is narrow for communication with fixed frequency and with frequency-hopping; however, the instantaneous frequency band for communication with direct spread-spectrum modulation is wide. The difference in the instantaneous frequency band can be utilized to carry out barrage type jamming in communication with direct spread-spectrum modulation.

With respect to direct frequency (or narrowband) jamming, it is the spot type jamming against communication at the conventional fixed frequency. However, with respect to communication with direct spread-spectrum modulation, this is barrage type jamming against communication with direct spread-spectrum modulation, as mentioned above.

A jamming machine sends single frequency (equal-amplitude sine waves) jamming or narrowband (noise) jamming. The jamming affects only one or several frequency channels in the fixed-frequency communication, but does not affect other frequency channels. In executing jamming, a jamming machine can select to carry out high-powered jamming against the particular frequency channel with the communication without fixed frequency in a

channel, thus, other fixed-frequency communication in this frequency will not be affected. Similarly, frequency-hopping communication in this frequency band is also not affected. Even if this jamming frequency channel is a frequency-hopper channel in frequency-hopping communication, since the jamming is against only one or several frequency-hopping channels in this frequency-hopping communication, basically normal communication will not be affected. However, in the case of high-powered single-frequency jamming or narrowband jamming, when the jamming frequency falls within the wide instantaneous frequency band in the signals of direct spread-spectrum modulation, effective jamming can be carried out for these communications with direct spread-spectrum modulation.

At the input terminal of a communication receiver, acoustic frequency jamming is the equal-amplitude sine wave jamming.

$$j_3(t) = J_\varepsilon \cos 2\pi f_{j3} t$$

Single-frequency jamming enters into the communication receiver, multiplication with the local oscillator signals of the frequency mixer and the receiver, the output jamming intermediate-frequency signal (the portion of the slip frequency),

$$j_{i3}(t) = \frac{1}{2} J_3 D \cdot p_0(t) \cos 2\pi (f_0 - f_{j3}) t$$

After this single-frequency jamming signal is subjected to frequency mixing, it is modulated with the rapid pseudocode sequence of the local oscillator, becoming a wideband jamming signal. The frequency width corresponds to the frequency width B_S of the local oscillator, and its energy frequency spectrum is distributed according to $(\sin x/x)^2$. For sake of simplicity in analysis, let us assume that the energy frequency spectrum of the jamming signal is homogeneously distributed. Since after mixing the bandwidth of the narrowband filter is B_{m}, when the long pseudocode sequence M>>N is adopted, the jamming energy P'_{J0}

passing through the narrowband filter is B_m/B_S of the total jamming energy P_{JI}.

To attain effective jamming, the separation coefficient is given by the formula: $K_{j3}'=N=B_s/B_m$

Actually, the jamming energy frequency spectrum is distributed according to $(\sin x/x)^2$, the energy density of the central part is higher than the energy density of the unmodulated frequency spectrum, by twice the amount. When the jamming carrier frequency is close to the center frequency of the signal, $f_S \approx f_{j3}$, the jamming energy P_{J0} passing through the narrowband filter is equal to $(2/N)P_{J1}$, then the separation coefficient $K_{J3}=N/2$. However, with increase in the carrier frequency difference, $\Delta f_{j3}=|f_S-f_{j3}|$, the separation coefficient also increases.

When jamming with a narrow band, the analysis is the same as when jamming with a single frequency.

During single-frequency jamming, it is not necessary to have the pseudocode sequence in enemy communication with direct spread-spectrum modulation, or the patterns of pseudocode sequence; it is also not necessary to know the technical parameters of the signal pseudocode rate; it is only necessary to know the center frequency [7] of enemy communication with direct spread-spectrum modulation by detecting signals. Therefore, single-frequency jamming is technically easier. When carrying out the jamming process, when the center frequencies of enemy communication of various channels with direct spread-spectrum modulation to be jammed are the same or close to each other, the jamming carrier frequency can be aimed at the center frequency of the signal. Thus, to attain the effective barrage type jamming, the required jamming power can be smaller. When the center frequency of the various channels in enemy communication to be

jammed is of direct spread-spectrum modulation, in order to attain uniform jamming effectiveness, we can assume several single-frequency (narrowband) jamming, and the carrier frequency of each jamming approaches the center frequency of enemy communication with direct spread-spectrum modulation near to several center frequencies.

With respect to a single frequency (narrowband) jamming against communication with direct spread-spectrum modulation, this is not absolutely the optimal jamming because it does not match the principle of absolute optimal jamming, that is, matching of the jamming frequency width with the signal frequency width. When the signal used by a receiver with direct spread-spectrum modulation differs in the frequency domain from the jamming signal, a cancellation technique against jamming with self-adaptive narrow band, and narrowband blanking wave technology, at the input terminal of the receiver the single-frequency (or narrowband) jamming can be effectively suppressed to carry on normal operation of communication even with direct spread-spectrum modulation.

V. Unmodulated Continuous-wave Barrage Type Jamming Against Communication With Direct Spread-spectrum Modulation

In the case of overall barrage type jamming, this means effective jamming applied to all communication channels in a frequency band with communication by direct spread-spectrum modulation, fixed-frequency communication, frequency-hopping communication, and hybrid communication with spread-spectrum modulation, in executing jamming.

Unmodulated continuous wave jamming is overall barrage type jamming; this is the absolute optimal barrage type jamming.

In the frequency domain, as the unmodulated continuous-wave

spectrum at a jamming frequency width can execute effective jamming at the same intensity against fixed-frequency communication of various channels, effective jamming of the same intensity can be carried out on various frequency-hopping channels of frequency-hopper with respect to communication in frequency-hopping. Similarly, the same-intensity effective jamming can be carried out against communication of various channels with direct spread-spectrum modulation (whether the carrier frequency is the same, or whether the length of the pseudocode rate and the pseudocode sequence are the same). Unmodulated continuous-wave jamming is the easiest to carry out technically, without requiring to know the real technical parameters of enemy communication with direct spread-spectrum modulation, but only to let the jamming frequency width cover the signal frequency width.

Let us assume that a communication receiver operates in fixed-frequency communication, and that the receiving bandwidth is B_m. Here, the signal power is P_c at the input terminal. To attain effective jamming, it is required that the jamming power Pjc be equal to the signal power $P_{jc}=P_C$, then it is required that the effective jamming power P_{j1} be equal to P_{jc} for the jamming B_m frequency width of the unmodulated continuous-wave jamming.

However, when the communication receiver operates with direct spread-spectrum modulation, the receiving bandwidth is increased to B_S, $N=B_S/B_m$. Let us assume at this point that the signal P_S at the input terminal is the same as the signal power of fixed-frequency communication, $P_S=P_C$. Here, however, due to the jamming function of unmodulated continuous-wave jamming, at the input terminal the jamming power $P_J=N \cdot P_{j1}-NP_S$.

This wideband jamming enters the receiver and is multiplied by the local oscillator signal of the frequency mixer and receiver. Since these two are not correlated, the output is

still the wideband jamming signal.

We can divide the input wideband jamming into N narrowband jamming of B_m frequency width with the same intensity. After multiplying with the local oscillator, the portion of the slip frequency of the various output jamming signals is

$$J_K(t) = \frac{1}{2} \cdot \sqrt{2P_{j1}} \cdot D \cdot p_0(t)\cos[2\pi f_{1K} t + \varphi_{jK}(t)]$$

$$f_{1K} = f_0 - f_{jK}, \ K = 1, \cdots\cdots, \ N$$

The frequency width of these output jamming signals $J_K(t)$ is B_S; the energy frequency spectrum is distributed according to $(\sin x/x)^2$. When the power of each output wideband jamming signal is P'_{JK}, and only a very small portion of jamming energy $P_{K0} \approx (1/N)P'_{JK}$ passing through the narrowband filter, the total output wideband jamming power $P'_J = NP'_{JK}$; however, the output jamming power P_{J0} passing through the narrowband filter is the summation of the jamming energy P_{K0}, only 1/N of the total jamming power.

$$P_{JO} = \sum_{K=1}^{N} P_{KO} \approx N \cdot \frac{P'_{JK}}{N} = P'_{JK} = P'_J / N$$

After the signal has the frequency mix, the output power $P_{SO} = K\dot{P}_S$ passing through the narrowband filter, then the post-frequency mixing jamming has the output power (passing through the narrowband filter) $P_{J0} = P'_J/N = kP_J/N = kP_S$. This output jamming power P_{J0} is equal to the output signal power P_{S0} to attain effective jamming.

From the foregoing analysis, we know that when effectively jamming a fixed-frequency communication at a single channel for the required jamming power P_1, in the situation with the same conditions of power and other parameters of the communication

station, and when effective barrage type jamming is carried out against fixed-frequency communication on N' channels, the required jamming power $P=NP_1$. However, the frequency width of $N'P_1$ for this power is used for unmodulated frequency spectrum barrage type jamming of N' channels, the jamming power is not required to be increased, capable of similarly conducting effective barrage type jamming on frequency-hopping communication over various channels with the same communication power. This is because effective jamming is carried out against communication with direct spread-spectrum modulation of N times the frequency for spread-spectrum modulation ($B_S/B_m=N$), the required jamming power is NP_1. However, this unmodulated frequency spectrum continuous-wave jamming is carried out in the N frequency width, and the jamming power is similarly NP_1 (when $N<N'$) [8].

With respect to a single communication receiver with direct spread-spectrum modulation, to attain effective jamming the unmodulated continuous-wave power at the receiver terminal should be N times the signal power, and the suppression coefficient is N.

As observed from another aspect, when sufficient power of barrage type jamming is available, unmodulated continuous-wave jamming has similar jamming effectiveness against all communications in the jamming frequency width (whether fixed-frequency communication, or communication with spread-spectrum modulation, and whatever the communication signal frequency band is wide or narrow.) This illustrates that, when carrying out overall barrage type jamming, the antijamming capability of communication with direct spread-spectrum modulation is not better than the antijamming capability against conventional communication.

Unmodulated continuous-wave jamming is adaptable to countermeasures in a densely concentrated signal environment.

The more the enemy communication networks requiring jamming, the more suitable is overall barrage type jamming. When the carrier frequencies are scattered in various channels with direct spread-spectrum modulation, even with different patterns of pseudocode sequences and different pseudocode rates, unmodulated continuous-wave jamming is the only effective barrage type jamming, especially suitable to the jamming of various communication, such as communication with direct spread-spectrum modulation, frequency-hopping communication, hybrid communication with spread-spectrum modulation, and fixed-frequency communication. For example, unmodulated continuous-wave jamming is suitable to adopt aerial jamming type and distributed jamming type as a barrage type jamming against land-based communication, or even high-frequency tactical communication [9]. For example, carrying out barrage type jamming against 6.4MHz wide battlefield tactical communication, ground jamming requires an effective irradiating power of 300kW (approximately the summation of power corresponding to 256 channels in spot type jamming) in attaining effective jamming. However, while adopting aerial jamming type, when the jammer is elevated, the required jamming power can be reduced. At a height of 2000m, the gain of elevation can be 40dB. Since ground jammers can adopt large high-gain wideband logarithmic periodic antennas, yet only small wideband low-gain antennas can be used while airborne. Even with the actual elevation gain is reduced to 34dB, with a wideband 6.4MHz jammer with output power of 150W and carried on a drone, overall effective barrage type jamming can be carried out against all important communication networks in the combat area, capable of enemy fixed-frequency communication, frequency-hopping communication, and also communication with spread-spectrum along with a hybrid of frequency-hopping direct spread-spectrum modulation. In the aerial jamming type, an aircraft can be used to penetrate the enemy air territory. In the distributed jamming type, the jammer can be projected into enemy territory, thus being capable of effectively jamming enemy communications at

lower jamming power, but basically not affecting our communications. During the Gulf War, the C^3CM tactics used against Iraq by the multinational forces led by the United States involved the application of hard weapons (such as cruise missiles) to destroy enemy targets with permanent destruction on the key enemy communication targets. However, the so-called electronic bombardment or electronic carpet was used to deal with large numbers of communication networks in order to choke the Iraqi combat command and communication system. Thus, enemy combat intelligence was unable to be reported to their headquarters, and combat orders were unable to be acted on so that the Iraqi vast war machine became a blind, deaf, and dumb giant. Large numbers of unorganized combat personnel, tanks, and cannons were helplessly destroyed and captured by the U.S. forces. Therefore, in the author's view, we should clearly understand the power of this barrage type jamming. Even with very good antijamming capability, such as field combat frequency-hopping communications and spread-spectrum hybrid communication against spot type jamming, these measures will be seriously hindered and unable to conduct normal communication with barrage type jamming.

VI. Properties of Various Jamming Systems Against Communication with Direct Spread-Spectrum Modulation

The active range, jamming parameters, separation coefficients, and other properties of various jamming systems against communication with direct spread-spectrum modulation are listed in the table below.

The carrier frequency difference is a jamming-technical parameter. In spot type jamming, the carrier frequency difference seriously affecting the jamming. Required by the waveform spot type jamming, the jamming carrier frequency should aim precisely at the signal carrier frequency. When the carrier

frequency difference Δf_j exceeds the signal frequency width B_m, the separation coefficient rapidly increases. In the case of unmodulated continuous-wave jamming, when the jamming frequency width covers the signal frequency width then there are no particular requirements on the carrier frequency difference.

The separation coefficient is a jamming-technical indicator. In the same kinds of jamming, the magnitude of the separation coefficient can reveal the jamming effectiveness. The jamming type with the smallest suppression coefficient is the optimal jamming type in the same kind of jamming. For example, in the correlated barrage type jamming, the greater the cross correlation between pseudocode sequences of jamming and communication signals, the smaller is the suppression coefficient. Correlation jamming with the smallest suppression coefficient is the optimal correlation jamming.

However, in different jamming types, the effectiveness of jamming is unable to be evaluated solely with the suppression coefficient. For example, with respect to unmodulated continuous-wave barrage type jamming, for jamming communication in a single channel with direct spread-spectrum modulation, the jamming power at the input terminal of the communication receiver is M times the signal power. Effective jamming is attained when the suppression coefficient is N. In the case of continuous-wave jammer, the required jamming power is NP_1. Within the same jamming frequency width, there is communication with multiple or even N channels with direct spread-spectrum modulation, with other conditions being equal, then it is not required to increase the jamming power. This wideband barrage type jammer with power NP_1 can simultaneously conduct effective jamming against communication of all these channels with direct spread-spectrum modulation. However, with respect to the waveform spot type jamming, even when the suppression coefficient is 1, effective

OPTIMAL JAMMING AGAINST COMMUNICATION WITH DIRECT-SPREAD SPECTRUM MODULATION

干扰样式 1	作　用 2	干扰参数 3	压制系数 4
波形瞄准式干扰 5 **	仅瞄准干扰特定信道的直扩通信 9	干扰参数完全和信号参数相同，载频瞄准，频宽重合，伪码序列相同且同步 13	$K_{J1} \approx 1$*
相关拦阻式干扰 6 **	对相近载频的各个信道直扩通信实施拦阻式干扰 10	干扰参数和信号参数相近，载频和伪码速率相近，伪码序列间互相关 14	$K_{J2} \geq \sqrt{N}$*
单频拦阻式干扰 7	仅拦阻式干扰载频相近直扩通信，不干扰定频、跳频通信 11	干扰和信号载频相近 15	$K_{J3} \approx N/2$* (当有抗窄带干扰措施时 $K_{J3} \gg N$)17
均匀频谱宽带拦阻式干扰 **	对干扰频宽内所有定频、跳频、直扩、组合扩谱通信实施拦阻式干扰 12	干扰频宽覆盖信号频宽 16	$K_{J4} = N$

* With increasing carrier-frequency difference, the suppression coefficient K_J should be increased.

** Absolute optimal jamming

KEY: 1 - jamming type 2 - function 3 - jamming parameters 4 - suppression coefficient 5 - waveform spot type jamming 6 - correlated barrage type jamming 7 - single-frequency barrage type jamming 8 - unmodulated continuous wave barrage type jamming 9 - communication with direct spread-spectrum modulation with jamming only aimed at particular channels 10 - barrage type jamming is carried out on communication in various channels near the carrier frequency with direct spread-spectrum modulation 11 - only barrage type jamming against communication of direct spread-spectrum modulation near the carrier frequency, not jamming against communication and frequency-hopping fixed-frequency 12 - barrage type jamming carried out against all communication in the jamming wave width, such as fixed-frequency, frequency-hopping, direct spread-spectrum, and hybrid spread-spectrum communication 13 - jamming parameters are identical with the signal parameters, with aiming at carrier frequencies, overlapping of frequency width, and same and synchronized pseudocode sequence 14 - jamming parameter is close to the signal parameter, close to the carrier frequency and pseudocode rate, with cross-correlation among pseudocode sequences 15 - jamming frequency is close to the signal carrier frequency 16 - jamming frequency width covers the signal frequency width 17 - (when there are countermeasures against narrowband jamming, $K_J3>>N$)

jamming can be carried out against communication with a single channel with direct spread-spectrum modulation. Here the jamming power is P_1 for a single type spot jammer. However, when there is communication with multiple channels for direct spread-spectrum modulation, other conditions being equal, it is required to correspondingly increase the number of spot type jammers, with a corresponding increase of total jamming power. In the case of communication of N channels with direct spread-spectrum modulation, N sets of spot jammers, and the total jamming power should be NP_1. In this situation, although the suppression coefficient of spot type jamming is better than that of barrage type jamming, however, for effective jamming with the same required total jamming power, the scale and cost of the N sets of spot type jammers is considerably greater than barrage type jammers. Even if they are all barrage type jammers, yet they are of different jamming systems. For example, with respect to correlation jamming and unmodulated continuous-wave jamming, similarly, the suppression coefficient is not the sole factor in evaluating jamming effectiveness.

Different types of jamming have different adaption ranges. In actual jamming for example, during combat which jamming system and types, or hybrid or multiple jamming systems are required? The answer is determined by multiple factors of enemy and our sides. Even if solely from the viewpoint of jamming systems, for minimum jamming costs in attaining the optimal comprehensive jamming effectiveness, jamming costs are related not only to jamming power, but also to the complexity and scale of reconnaissance and jamming equipment in combat, in addition to the quality and number of operators, as well as the total cost of power supply and equipment.

The article studies mainly the jamming of signal transmission with direct spread-spectrum modulation. Another paper [10] shows the details of studying the jamming of

synchronizing communication systems with direct spread-spectrum modulation. The synchronizing system is an important integral of communication with direct spread-spectrum modulation. While jamming against synchronizing communication systems with direct spread-spectrum modulation is easier than jamming against communication signal systems with direct spread-spectrum modulation, jamming against the synchronizing system should be the main jamming approach against communication with direct spread-spectrum modulation. Therefore, the jamming study against the synchronizing system of communication with direct spread-spectrum modulation should be similarly emphasized.

With respect to jamming against communication with direct spread-spectrum modulation, in the search and synchronizing stages in communication with direct spread-spectrum modulation, when effective jamming is attained, the communication receivers will be unable to synchronize with signals to enter the signal receiving state, or even to have pseudosynchronization with jamming for pseudoreception. When the signal receiving stage of communication with direct spread-spectrum modulation is jammed, as the above-mentioned analysis shows, jamming increases noise in the signal system to lower the signal-to-noise ratio, leading to deteriorating the communication quality. At the same time, jamming will deteriorate the performance of the synchronizing system, to make it deviate from full synchronism so that the signal level of the system is lowered, and further lowering the signal-to-noise ratio, leading to further deterioration of communication quality. Therefore, the gain treatment for communication with direct spread-spectrum modulation is not determined only by the treatment gain of the signal system, but is also determined by the treatment gain of the synchronizing system. Generally, such treatment gain of communication with direct spread-spectrum modulation is lower than the treatment gain of the signal system. However, against the synchronizing system by the communicating side in carrying out jamming, the

synchronizing system should be developed and improved so that the synchronizing system is developed to adapt to the signal system, and to ensure that the synchronizing system has the capability against jamming, or at least that it has antijamming capability not lower than the signal system. In this situation, we can say that the jamming study against communication with direct spread-spectrum modulation is mainly a study of optimal jamming against the communication signal system with direct spread-spectrum modulation.

VII. Conclusions

There are two major jamming systems against communication with direct spread-spectrum modulation: spot type jamming and barrage type jamming. Spot type jamming is still in the exploratory study stage. At present, the effective jamming system is barrage type jamming. The absolute optimal barrage type jamming is mainly correlation jamming and unmodulated continuous-wave jamming.

Correlation jamming is suitable in conducting barrage type jamming against communication in various channels with direct spread-spectrum modulation near the carrier frequency. Jamming effectiveness increases with increase in cross correlation among pseudocode sequences of the jamming and signals. With respect to this point, the jamming side should mainly understand the patterns of pseudocode sequence of various series of communication with direct spread-spectrum modulation to stress research on jamming pseudocode sequences and related technical parameters for jamming with the maximum cross correlation that a signal pseudocode sequence can generate in order to attain optimal correlation jamming. However, unmodulated continuous-wave jamming is suitable to densely concentrated signal environments to carry out barrage type jamming against multiple channels with distributed signal carrier frequencies against

communications at fixed-frequency, frequency-hopping, direct spread-spectrum, and hybrid spread-spectrum types. Therefore, the jamming side should stress the study of various optimal jamming types (such as aerial jamming and distributed jamming), and to carry out overall barrage type jamming against different communication objects in order to attain the optimal comprehensive jamming.

REFERENCES

1 徐穆洵、章丕. 通信干扰最佳干扰理论的研究. 通信对抗. 1987;4

2 徐穆洵. 通信对抗. 通信对抗. 1984;1

3 R.C.DIXON. Spread Spectrum System. 1976

4 徐穆洵. 跳频通信对抗的研究. 军事通信技术. 1993;2

5 徐穆洵. 对 GPS 的干扰. 中国电子学会导航分会第四届学术年会论文集. 1993;5

6 Jack K.Holmes. "Coherent Spread Spectrum Systems", 1982

7 徐穆洵. 对直扩通信信号的平方倍频检测. 通信对抗. 1994;1

8 徐穆洵. 通信阻塞式干扰. 通信对抗. 1991;4

9 徐穆洵. 阻塞式干扰的综析. 通信对抗. 1981;2

10 徐穆洵. 对直扩通信同步系统干扰研究. 内部资料. 1994

DISTRIBUTION LIST

DISTRIBUTION DIRECT TO RECIPIENT

ORGANIZATION	MICROFICHE
B085 DIA/RTS-2FI	1
C509 BALLOC509 BALLISTIC RES LAB	1
C510 R&T LABS/AVEADCOM	1
C513 ARRADCOM	1
C535 AVRADCOM/TSARCOM	1
C539 TRASANA	1
Q592 FSTC	4
Q619 MSIC REDSTONE	1
Q008 NTIC	1
Q043 AFMIC-IS	1
E404 AEDC/DOF	1
E410 AFDTC/IN	1
E429 SD/IND	1
P005 DOE/ISA/DDI	1
1051 AFIT/LDE	1
P090 NSA/CDB	1

Microfiche Nbr: FTD96C000087
NAIC-ID(RS)T-0477-95